DEPTHS OF SEGREGATION OF HI-TIO$_2$ PICRITE MARE GLASSES P. C. Hess, A. Finnila, Department of Geological Scieneces, Brown University, Providence, RI 02912 U.S.A.

Pristine mare glasses are among the most primitive liquid compositions yet discovered on the moon and consequently are the best candidates for primary magmas (1,2). A potentially important constraint to their petrogenesis is provided by the liquidus phase relations which show that pristine mare glasses are multi-saturated with respect to olivine + orthopyroxene at pressures between 2.0 to 2.5 GPa but have only olivine or orthopyroxene on the liquidus at lower and higher pressures respectively (3,4,5). If the mare glasses are products of small degrees of melting, the conventional interpretation is that these melts were produced from a source in which olivine and orthopyroxene were restite phases. Such sources are very deep seated, however, and make melt extraction a difficult problem. But this interpretation is not unique, of course. During the overturn of the unstable cumulate layer (6) it is quite possible that small amounts of late stage ilmenite-rich cumulates were mixed with either dunite or orthopyroxenite units. Small degrees of melting would eliminate the mare basalt components and leave only olivine or orthopyroxene in the source. Given these possibilities, the phase equilibria provide no constraints to the depths of petrogenesis. We report here, however, new phase equilibria constraints that lend support to the original multi-saturation hypothesis.

Piston-cylinder experiments at pressures from 1.0 to 2.0 GPa were performed to determine the P-T dependence of the composition of ilmenite saturated mare basalts. Our data show that there is only a weak pressure dependence but a strong temperature dependence on the solubility of ilmenite. At 1.0 GPa, for example the TiO$_2$ content of ilmenite saturated mare basalt (Apollo 15 red glass) increases from about 17 wt% TiO$_2$ at 1255°C to 30 wt% TiO$_2$ 1375°C, or about 0.1 wt% per °C (Fig. 1). While these data do not directly apply to multi-saturated ilmenite bearing melts, it is easy to infer that some high Ti mare basalts are significantly undersaturated with respect to ilmenite. The orange picrite glass, for example, contains 9% TiO$_2$ a value that is less than 33% of that needed to saturate ilmenite at the appropriate liquidus temperatures ~1350°C. These data support the phase equilibria studies which do not have ilmenite on or near the liquidi of picrite mare glasses (7). It follows that any ilmenite originally present in the source was totally consumed during the generation of the picrite glasses. While some estimates of modal ilmenite originally in the source regions run as high as 10% (8) such high values are unrealistic because they would require 30% or more melting to eliminate ilmenite from the source. Such large degrees of melting are difficult to reconcile with the trace element data (9). Phase equilibria studies prove that high Ti mare glasses are undersaturated not only with respect to ilmenite but also with respect to high CaO-pyroxene and plagioclase. We will now argue that these primitive mare melts were saturated with both olivine and low Ca pyroxene at their source.

Our experimental results provide the necessary data to approximate the phase diagram to understand the petrogenesis of mare basalt. We take the MgO-SiO$_2$-TiO$_2$ ternary liquidus at high pressure as the most useful template for our discussions (10). This phase diagram has a prominent olivine-enstatite cotectic that is near radial to the TiO$_2$ apex. Melts generated along this cotectic show an inverse relation between TiO$_2$ and MgO, as observed in the mare glasses (1). We project our experimental liquids saturated with respect to ilmenite or ilmenite + olivine from CaAl$_2$Si$_2$O$_8$ and CaMgSi$_2$O$_6$ onto the (MgO-FeO)-SiO$_2$-TiO$_2$ pseudoternary diagram. Theoretical analysis (11) shows that projecting through normative rather than oxide components does least to perturb the correct phase relations. We use the olivine-enstatite cotectic from (15) and constrain the enstatite-ilmenite cotectic with the help of Schreinemaker's rules and the slope taken from the TiO$_2$-enstatite cotectic in the MgO-SiO$_2$-TiO$_2$ system.

The compositions of the high TiO$_2$ mare glasses projected in the same manner all fall on or very near to the olivine-orthopyroxene cotectics between 1.5 and 2.5 GPa. (Fig. 2). Certainly, the loci of points lie parallel to the trend of the cotectic. This near coincidence between projected points and phase equilibria is strong evidence that high-TiO$_2$ picrite melts were extracted from a source having olivine-orthopyroxene in the restite. Indeed, there is no convincing alternative hypothesis (see also (8)). We conclude, therefore, that high Ti mare glasses are near primary liquids derived from an olivine-orthopyroxene source with an average depth of segregation of about 400 km.

Density inversions between very high TiO$_2$ mare basalt and the lunar mantle which were first predicted by Delano (12) and confirmed by experiment by Circone and Agee (13) indicate that such melts become buoyant at depths less than 400 km. Perhaps it is no coincidence that the average depths of multi-saturation and the

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maximum depths for buoyant rise correspond. Below these depths, Hess (2) has argued that even negatively buoyant melts can rise with ascending diapirs provided the latter have a minimum ascent velocity. Negatively buoyant melts also can be carried upwards in buoyant plumes if the melts wet only some crystal-crystal boundaries and because sinking melts would crystallize as they descend along their adiabats (see also(13)).

Perhaps a more severe problem is how to preserve the high pressure signature of such melts. In most models, such melts must be isolated, perhaps in large-enough melt pockets, to prevent their equilibration with a shallow mantle (14). Perhaps this is the correct model. In any case, appropriate models for melt ascent from great depths must exist - high TiO_2-mare basalts have largely equilibrated with deep-seated cumulates.

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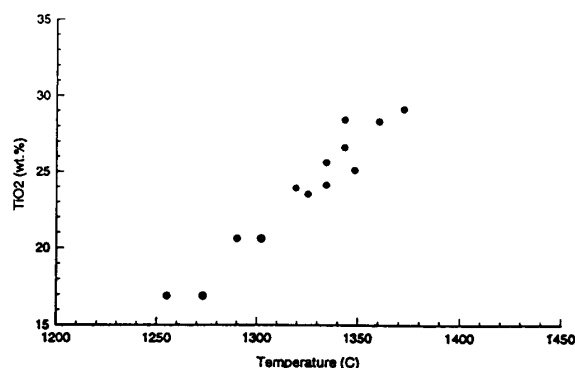
Fig. 1. TiO_2 content of ilmenite saturated mare liquids (Apollo 15 Red Glass).
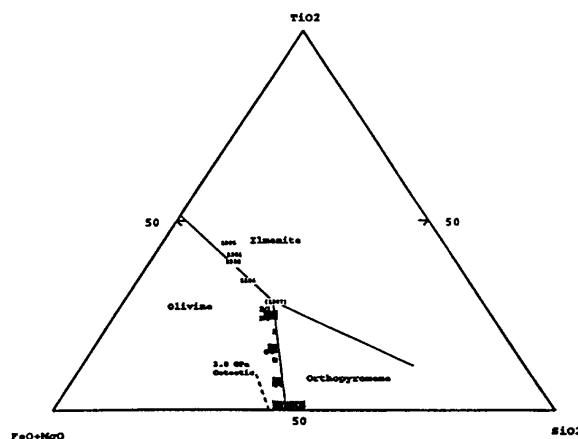
Fig 2. Phase diagram at 1.5GPa giving the olivine-orthopyroxene cotectic and compositions (dark squares) of mare picrite glasses projected from $CaAl_3Si_2O_8 + CaMgSi_2O_6$. Dashed line 3.0 GPa cotectic. Numbers are temperatures and compositions of olivine-ilmenite saturated melts.